A New Scheme for Acoustical Tomography of the Ocean

Alexander G. Voronovich
NOAA/ERL/ETL, R/E/ET1
325 Broadway
Boulder, CO 80303
phone (303)-497-6464 fax (303)-497-3577 email agv@etl.noaa.gov

E.C. Shang
NOAA/ERL/ETL, R/E/ET1 325 Broadway, Boulder, CO 80303
phone (303)-497-6363 fax (303)-497-3577 email eshang@etl.noaa.gov
Award #: N00014-95-F-0046
http://www.etl.noaa.gov

LONG-TERM GOALS

The long-term goal is to develop a remote sensing technique to infer ocean inner 3-D structure using acoustical means. This technique should provide an affordable mean of studying ocean dynamics on different temporary and spacial scales.

OBJECTIVES

The objective is to develop a new robust scheme of the acoustical tomography of the ocean of meso- to global scales which is able to infer a 3-D ocean inner structure using simple tonal low-frequency acoustic signals and vertical line receiving arrays. The inversion scheme should be based on measurements of horizontal refraction angle (HRA) related to different acoustic modes rather that travel time along different rays. Both inhomogeneity of the sound speed field and ocean current should be retrieved.

APPROACH

In spite of its small value HRA angle can be easily measured with the help of a pair of mode-resolving line vertical arrays situated about 10 km apart (ocean interferometer). In the simplest case mode interaction can be neglected, and HRA are inverted into sound speed profiles assuming adiabatic propagation. The inversion proceeds in two stages: 1) 2-D tomography which retrieves propagation constants of different modes at the nodes of horizontal rectangular grid covering the area. 2) 1-D tomography which retrieves sound speed profile (in terms of expansion with respect to a set of empirical orthogonal functions) at each node of horizontal grid based on already determined values of propagation constants.

In the general case, acoustic mode interaction due to water mass inhomogeneity should be taken into account. This is accomplished with the help of iterations. In the first approximation the propagation is assumed to be adiabatic and inversion proceeds according to the “adiabatic” inversion scheme. Then the contribution to horizontal refraction due to mode interaction are calculated with respect to the retrieved inhomogeneous medium using propagation code which takes into account mode interactions in the $N \times 2D$ approximation. These corrections are subtracted from the data on HRA (one can say, that

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **A New Scheme for Acoustical Tomography of the Ocean**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Oceanic and Atmospheric Administration (NOAA),Environmental Technology Laboratory,325 Broadway,Boulder,CO,80303**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

propagation is thus made “closer to adiabatic”), and the procedure of adiabatic inversion is repeated with the corrected set of data. When converges, this procedure provides sound speed field which is consistent with the acoustical HRA data.

The real experiment might look as follows. A low frequency tonal sound source(s) (F = 30-100 Hz) is assumed to be towed by a vessel(s) around the area of interest with typical horizontal scale of the order of 1000 km. The transmitted signal is received by acoustic interferometers located inside or outside the area. Thus, the area is exposed from different directions, and HRA is known as a function of source position. Those data are then used for calculation HRA and tomography inversion.

WORK COMPLETED

This part of work completes theoretical development of the Horizontal Refraction Modal Tomography inversion scheme, and below we briefly summarize all major accomplishments of the project. The work done during FY99 was related mainly to the extension of the inversion scheme for inferring ocean currents using the same approach we exploited so far for sound speed field reconstruction. The method of currents inference was successfully applied to the Fram Strait environment.

The adiabatic inversion scheme described above was developed. The approach described above was realized as a software package that consisted of a number of codes. Those codes generate a 3-D inhomogeneous sound speed according to the ocean model assumed, calculate acoustic propagation through this medium along multiple routes connecting transmitter and receivers, process simulated HRA data to infer a 2-D field of propagation constants at the nods of a grid (the first stage of inversion), processing propagation constant data to infer sound-speed profiles at those nodes, and comparing the results of inversion to the initial sound speed filed. Those codes were used in an appropriate sequence according to the adiabatic or non-adiabatic (iterative) mode of inversion.

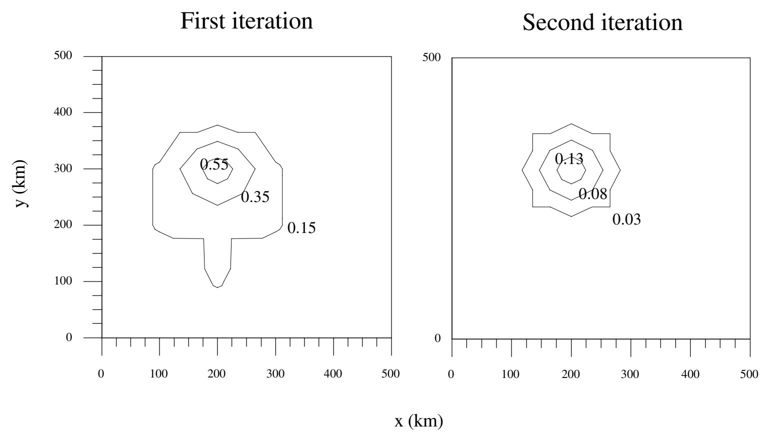
Mention, that our simulation included extensive solution of the direct propagation problem with accurate enough calculation of the modal phases. To achieve this, we used an efficient non-parabolic marching algorithm developed previously with the support from ONR for another project. This allowed us to perform all calculations fast enough using standard PC.

Different sources of errors such as navigation errors, acoustic noise, scattering at internal waves, etc. were analyzed. The most significant problem is taking into account in an accurate way such an important factor as scattering of acoustic signals at internal waves. For sufficiently low frequencies applied in our tomography scheme an adequate analytical approach to the description of this process was developed. Another problem in the practical cases could be bottom-interaction. Towards this effect we elaborated appropriate generalization of the aforementioned non-parabolic propagation code.

RESULTS

Appropriate numerical simulations were performed with the help of software developed. Both model “Gaussian” eddies imbedded into homogeneous ocean with Munk canonical profile and Atlantic “meddy” which was measured experimentally in 1991 to the west of Gibraltar were used for simulations. In the latter case the sound speed profiles included double-channel situation which often gives rise to strong mode coupling. We found, however, that even when the correction to the phases of the acoustic modes is significant, mode interaction weakly affects the HRA, because the corrections cancel out upon subtracting phases at two vertical arrays composing the acoustic interferometer.

However, for some propagation paths interaction-induced HRA correction was appreciable. Nevertheless, the inversion according to the iterative scheme performed successfully. In the error-free situation the solution required three iterations. The first iteration corresponded to the maximum error in the sound speed retrieval of about 0.5 m/s, the second iteration produced an error of 0.1 m/s, and the third iteration converged to the exact solution. The figures below demonstrate the results of retrieval for the first and the second iteration. The difference between exact and retrieved sound speed profiles (maximum over depth in m/s at a given point on horizontal plane) is plotted as in terms of contour lines.



In the case of the data distorted by internal waves scattering effects the inversion in the adiabatic case resulted in an error of 0.7 m/s. This inversion scheme was also successfully applied to different situations including the case of frontal zone and internal waves solitons. Those results are reported in [6], [10-12].

IMPACT/APPLICATIONS

The main conclusion resulted from this work is that the suggested acoustic tomography inversion scheme based on measurements of horizontal refraction angles is feasible and can be practically used. Potential applications of the HRT for acoustic tomographic inversion of ocean frontal structure and solitons in coastal area are also promising.

Horizontal refraction modal tomography offers some advantages in retrieving a 3-D profile of a sound-speed field of an area with respect to time-of-flight-based inversion schemes. In particular, the profile can be made relatively fast (for the time which is necessary for the vessel(s) to go around the area). Highly accurate recording of source position or time is not necessary. Low-power easy-to-generate CW signals can be used for sounding. The most important part of the inversion (first stage) is a completely linear, standard procedure. Thus, interpretation of data is significantly simplified. There is no need for "initialization" (i.e., no information about the sound-speed field in the area at the initial moment of time is required). The value of the error in retrieving a SSP (which is about 0.5 m/s for the conservative estimate of the errors associated with scattering at internal waves involved) seems to be acceptable.

RELATED PROJECTS

An exact non-parabolic algorithm developed within the project "Non-parabolic marching algorithm for sound field calculations in the inhomogeneous ocean waveguide" was used for numerical simulations taking into account mode interactions.

PUBLICATIONS

The list of publications includes all major papers appeared as a result of this project effort.

1. A.G. Voronovich and E.C. Shang 1995: “A note on horizontal-refraction-modal tomography,” J. Acoust. Soc. Am., v.98, 2708-2716.
2. A.G. Voronovich and E.C. Shang 1997: “Numerical simulations with horizontal-refraction-modal tomography. Part I. Adiabatic Propagation”, J. Acoust. Soc. Am., v. 101, 2636-2643.
3. E.C. Shang 1997: "Ocean acoustic thermometry and tomography", J. Ocean Univ. Qingdao, v. 27, No. 1, 1-15.
4. E.C. Shang, Y.Y. Wang and A.G. Voronovich 1997: "Nonlinear tomographic inversion by using WKB modal condition", J. Acoust. Soc. Am., v.102, 3425-3432.
5. A.G. Voronovich and E.C. Shang (1999): “Horizontal refraction modal tomography of the ocean with mode interaction”, IEEE JOE, v. 24, 224-230.
6. E.C. Shang, A.G. Voronovich, Y.Y. Wang, and L.A. Ostrovsky 1998: “Application of modal horizontal-refraction tomography and modal phase tomography for ocean remote sensing.” Proc. of PORSEC’98, 698-702.
7. A.G. Voronovich 1998: “Low-frequency sound propagation through random internal waves with application to measurements of internal wave spectra by acoustic means,” Proc. of the Fourth European Conf. on Underwater Acoustics, Ed. By A. Alippi and G.B. Cannelli, v. II, 751-756, Rome.
8. E. C. Shang, A. G. Voronovich, and Y.Y. Wang 1999: “Progress in Modal Phase Tomography (MPT) and Modal-Horizontal-Refraction Tomography (MHRT) for Ocean Monotoring,” Proceedings of *International Symposium on Acoustic Tomography and Acoustic Thermometry,* pp.56-62, Tokyo, Japan.
9. E. C. Shang, A.G. Voronovich, Y.Y. Wang, K. Naugolnykh, and L. Ostrovsky, “New Schemes of Ocean Acoustic Tomography,” (accepted for publication by J. Comput. Acoust.)
10. E.C. Shang, Y.Y. Wang, “The frontal effects on long-range acoustic propagation in the North Pacific Ocean”, (JASA, in press).
11. K. A. Naugolnykh, Y.Y. Wang, and E.C. Shang, “Numerical Simulation of Transverse Current Monitoring in Fram Strait,” (submitted to IEEE-JOE).
12. E.C. Shang and Y.Y. Wang, “Tomographic Inversion of Ocean Front,” (submitted to the 5th European Conference on Underwater Acoustics, July 10-13, 1999, Lyon, France)